DESIGN AND TESTING OF S-31 BRIDGE REPLACEMENT PROJECT USING RAPID CONSTRUCTION METHOD

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ABSTRACT

SCDOT plans to replace 5 bridges on S-31 in Horry County, South Carolina. This project is located near the most seismically active area on the east coast. This project was awarded a grant by FHWA to deliver the project via rapid construction method. The bridges were designed using precast superstructures and substructures. The superstructures consisted of precast solid slabs with transverse post-tensioning. The substructures utilized precast bent caps and concrete piles. The bridges were designed for seismic loading and earthquake induced liquefaction. Parallel to design, SCDOT granted University of South Carolina to perform testing of precast bent cap and pile connections. Two full-scale single pile to precast bent cap connections were tested. Specimens were created by plainly embedding each pile to a pocketed precast bent cap, with a closure pour finalizing the connection between the two elements. Specimens were subjected to displacement controlled reverse cyclic loading to ±8.0 inches. Results were presented in terms of moment capacity, ductility, plastic hinge length, confining stress, and cap performance. Results showed that the design of the bent caps provides adequate confinement to the embedded pile yielding exceptional seismic performance. The testing recommendations were incorporated into the final design of the bridge substructure.

Keywords: Precast superstructure, Post-tensioning, Precast bent cap, Precast concrete pile, Bent cap connection, Seismic design

1. Introduction

South Carolina Department of Transportation (SCDOT) plans to replace five bridges on a secondary route S-26-31 over the Waccamaw River Swamp in Horry County, 9 miles northwest of Myrtle Beach, South Carolina. These 2-lane rural bridges were originally designed to carry an H-10 live load and were built approximately 50 years ago. All five bridges have been determined by SCDOT to be functionally obsolete and structurally deficient with sufficiency ratings ranging from 18.2 to 38.6. Currently these bridges carry 4,200 vehicles per day. The existing bridges consist of multiple 15' spans of precast deck panels supported on timber pile bents. In order to minimize the impact to the Waccamaw River Swamp, the bridges will be reconstructed on the existing alignment, while sections of the road are closed to through traffic with a detour to SR 22 Conway Bypass. This project is located approximately 75 miles from Charleston, the most seismically active area on the east coast of the United States.

SCDOT directed the consultant STV/Ralph Whitehead Associates, Inc. (STV) to study the bridge types and identify the most feasible options with considerations of safety, traffic control, construction schedule, constructability and estimated costs. Among the factors listed above, construction schedule and estimated cost were the driving factors with due consideration of other issues. It is SCDOT's priority to minimize the disruption to the traffic and impact to the properties along this 2.5 miles stretch of the road. STV studied various types, such as precast deck slabs with concrete pile bents, flat slab bridge with concrete pile bents, and precast AASHTO girder bridges. The use of precast bridge elements has become an increasingly popular means of accelerating bridge construction. The use of precast bent caps reduces construction time and costs. After completing bridge type study, STV recommended precast bridge systems, using both precast superstructure and substructure. Subsequently, this project was awarded a grant by FHWA to deliver the project via rapid construction method.

The bridges were designed using AASHTO LRFD Bridge Design Specifications (AASHTO LRFD) and 2008 SCDOT Seismic Design Specifications for Highway Bridges, Version 2 (SCDOT Seismic Specs). The design of superstructures consists precast solid slabs with concrete topping. The substructures utilize precast bent caps and concrete piles. The bridges were designed for seismic loading and earthquake induced liquefaction.

In conjunction with structural design, SCDOT granted the University of South Carolina at Columbia to perform testing of representative precast bent cap and pile connections. Two full-scale single pile to precast bent cap connections were tested. Specimens were created by plainly embedding each pile into a pocketed precast bent cap, with a closure pour finalizing the connection between the two elements. Specimens were subjected to displacement controlled reverse cyclic loading to a maximum value of ±8.0 inches. Results are presented in terms of moment capacity, ductility, plastic hinge length, confining stress, and cap performance. Results show that the design of the bent caps provides adequate confinement to the embedded pile yielding adequate seismic performance. The testing recommendations were incorporated into the final design of the bridge substructure.

This project was recently awarded to a low bidder and the construction of the bridge and approaching roadway has recently initiated.

2. Bridge Design

These five bridges were designed to carry two 12 ft travel lanes and 8 ft shoulders. The total superstructure width is 43 ft and 3 inches. Based on the results of a hydraulic study, bridge openings were required from 40 ft to 80 ft. In order to minimize future maintenance and enhance performance of the deck slab, consideration was given to make the superstructure continuous for live load over interior bents. Therefore, Bridges 1-4 were designed using a two span configuration without any joints over interior bents. Bridge 5 is a single span bridge. The span arrangements of the above bridges are:

- Bridge 1: 30 ft + 30 ft made continuous for live load over interior bent
- Bridge 2: 30 ft + 30 ft made continuous for live load over interior bent
- Bridge 3: 30 ft + 30 ft made continuous for live load over interior bent
- Bridge 4: 40 ft + 40 ft made continuous for live load over interior bent
- Bridge 5: 40 ft single span

The superstructures consist of precast solid slabs with 5 inches minimum thickness of concrete topping. After erection of the precast slabs, shear keys will be poured between solid slabs and transverse post-tensioning will be performed to achieve lateral stiffness. After post-tensioning is installed, the top of the precast slab becomes a drive-able surface. The concrete topping is then poured over the precast slabs. See Figure 1 for typical bridge sections. One mat of reinforcement is provided in the concrete topping. In order to reduce future maintenance, the superstructures are designed to make precast slabs continuous for live load over interior bents. Adequate longitudinal reinforcement over the interior bents was designed to achieve continuity for live load.

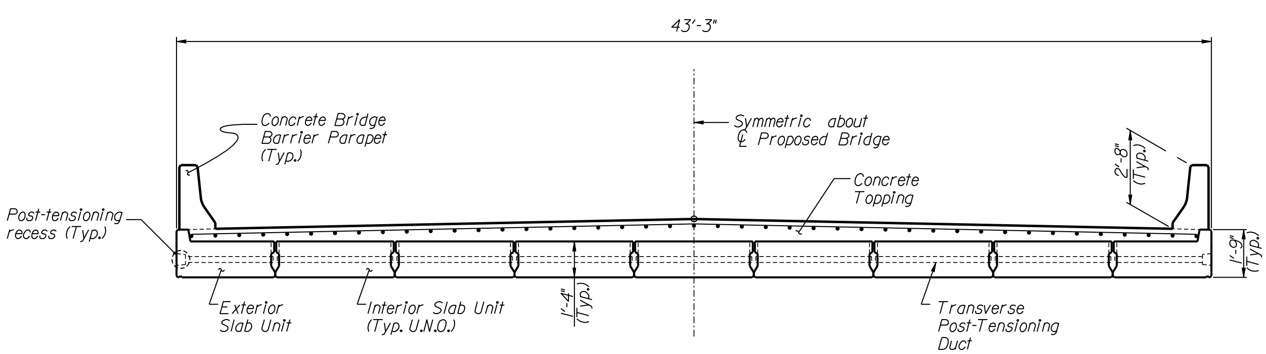
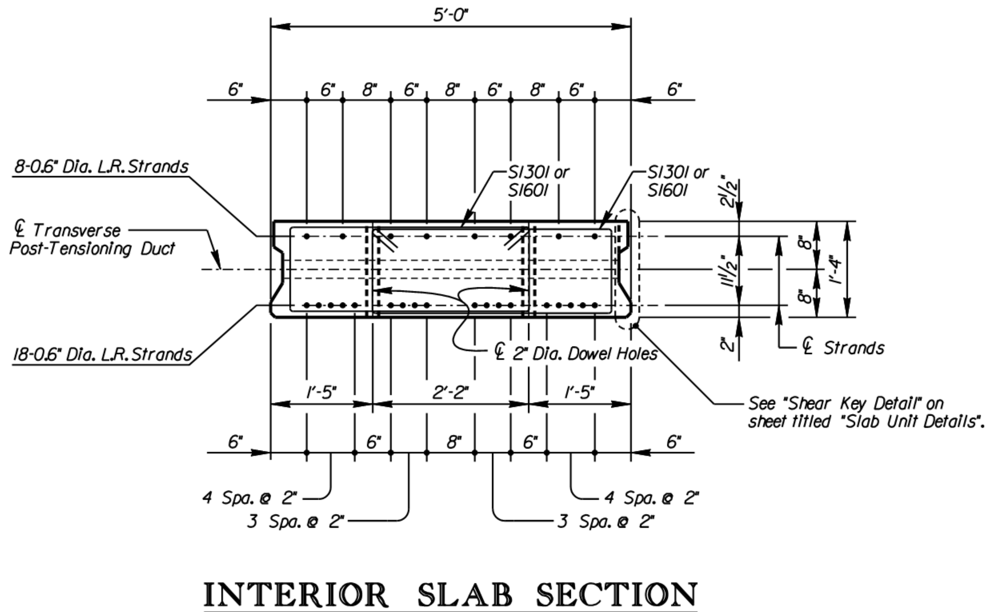


Figure 2 Typical Section

The precast solid slabs were designed using Class 7000 concrete with 28 days compressive strength of 7,000 psi, prestressed with 0.6 inches low relaxation strands.

The precast solid slabs were also analyzed for both simple span condition and continuous for live load condition in accordance with SCDOT design policy. In transverse direction, post-tensioning tendons were designed to tie all the slabs together. 4 and 5 tendons were used for 30 ft and 40 ft spans, respectively. Each tendon consists of 4 -0.6 inch low relaxation strands. Figures 2 shows typical interior and exterior slab units. Figure 3 shows shear key and post-tensioning duct splice details.



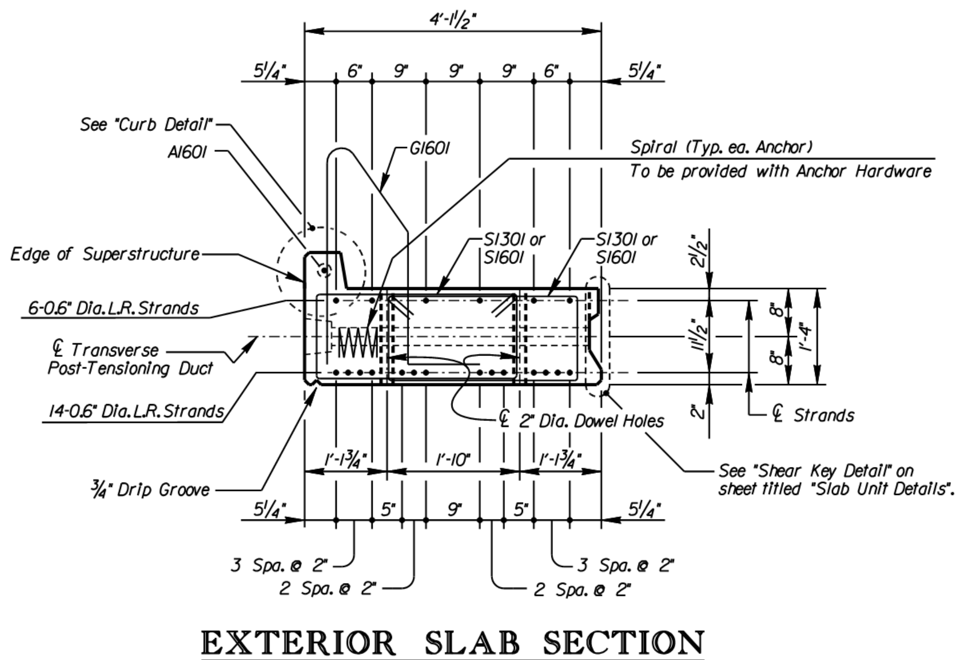


Figure 2 Precast Solid Slab Typical Sections

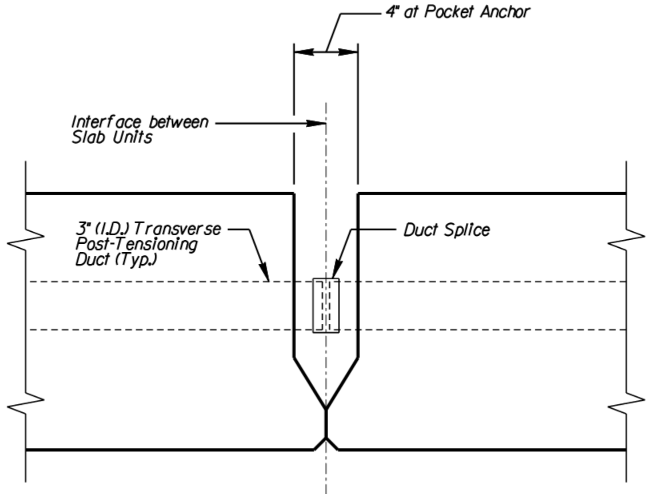


Figure 3 Shear Key and Post-tensioning Duct Splice Details

The substructure consists of precast concrete bent bap and precast concrete piles. The pocket holes in the bent caps are filled with concrete grout. See Figure 4 for a typical bent configuration. The pockets in the precast bent caps are 3 ft in diameter to accommodate the 20 inches square pile heads. 26 inches of pile embedment was recommended based on the testing reports prepared by University of South Carolina (Ziehl et. al 2011). Therefore a 4 ft and 6 inches wide and 3 ft and 6 inches deep cap was chosen. The total cap length is 45 ft. If the cap was designed using one piece, the total weight would be approximately 106 kips. In order to reduce the shipping and handling weight, a 4 ft closure pour was introduced so each piece of the cap was reduced to approximately 48 kips. 4,000 psi concrete will be used for closure pour to match the precast bent caps.

Due to soft soil and relatively high seismicity, seismic design of these bridges became difficult to satisfy the displacement demand limits, displacement capacity, and ductility requirements prescribed in SCDOT Seismic Specs. The seismic design parameters are listed below:

- Seismic Design Category: C
- Analysis Method: Multimode Spectral Analysis with Pushover (except Bridge 5)
- Operational Classification: II
- Site Class: E
- Design Acceleration Coefficients:

    PGA (FEE): 0.14g
    S_{DS} (FEE): 0.29g
    S_{D1} (FEE): 0.16g
    PGA (SEE): 0.35g
    S_{DS} (SEE): 0.84g
    S_{D1} (SEE): 0.60g

See Figure 5 for acceleration design response spectrum (ADRS) curves.

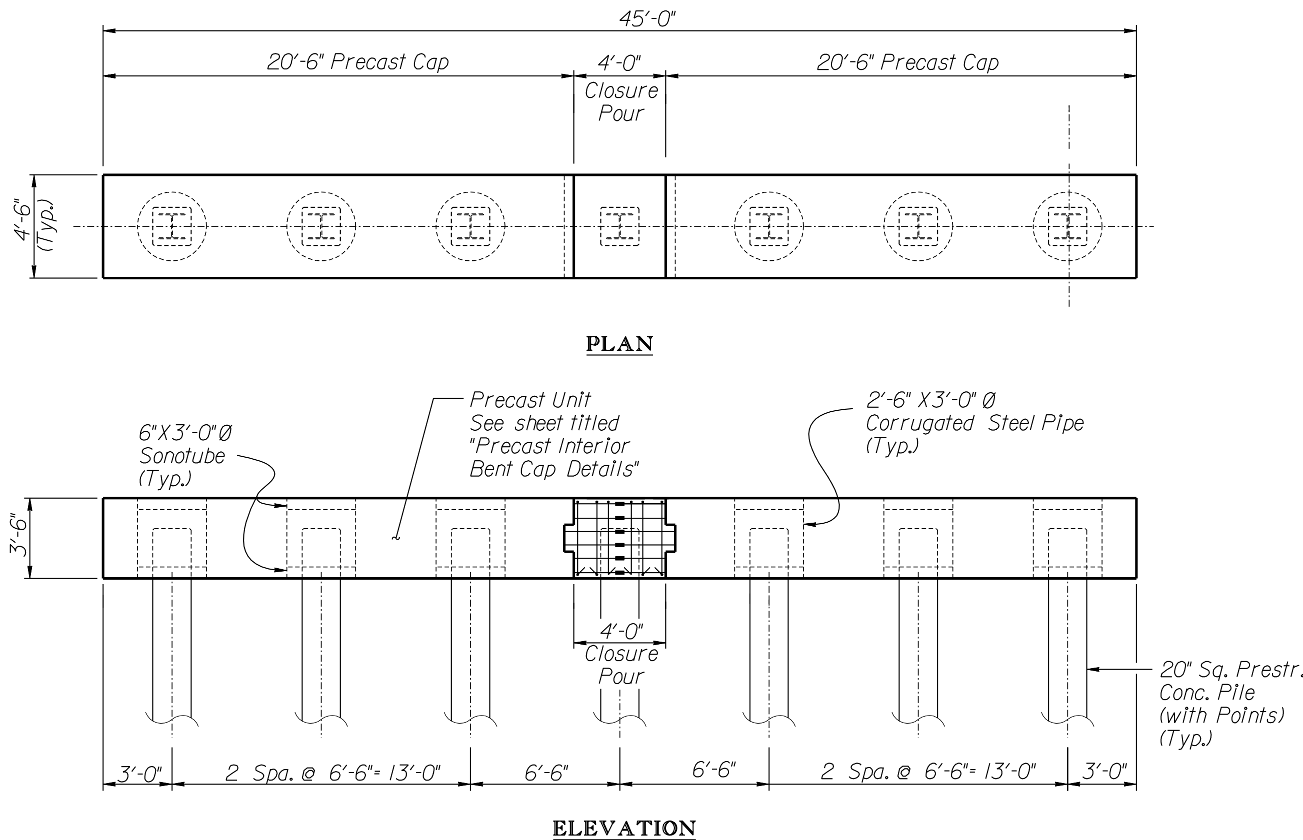


Figure 4 Typical Substurcutre Unit

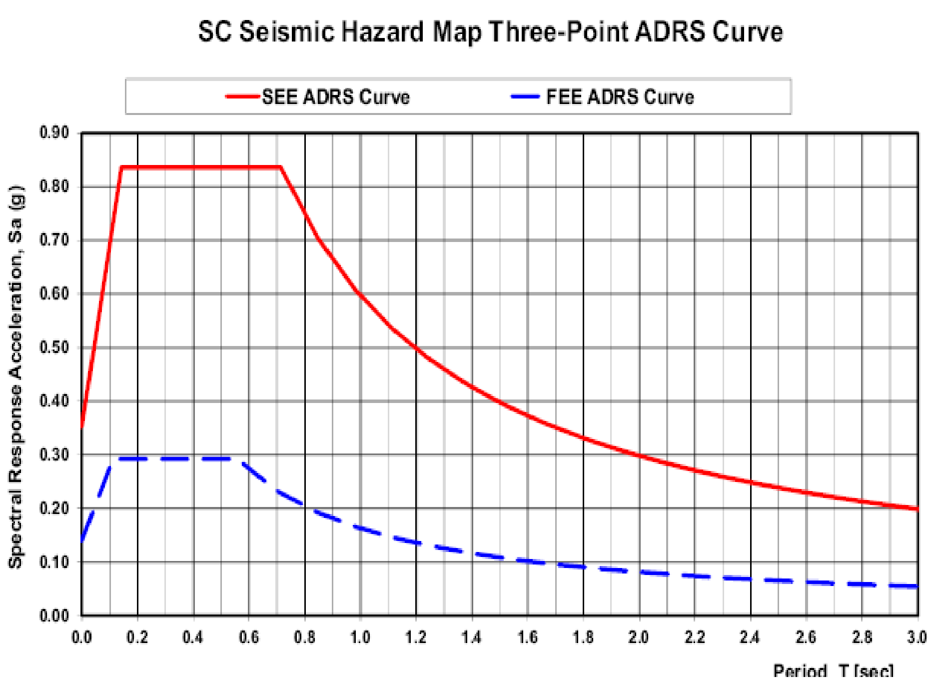


Figure 5 Acceleration Design Response Spectrum Curve

Due to soft soil, large seismic displacement demands were anticipated. Prestressed concrete pile bents typically present difficulties in seismic design due to limited ductility capacity, relatively smaller shear capacity, and the nature of the connection between the pile head and bent cap.

Multimode spectral analyses were performed for all two span bridges via SEISAB program. 25 modes were analyzed to achieve higher than 90% of mass participation.

The seismic displacement demands in both longitudinal and transverse directions are approximately 6" from design calculations. SCDOT Seismic Specs prescribed the displacement limits for various design components and for various bridges with different operational classifications. In comparing the displacement demand and displacement capacity, the design satisfies all the displacement limits. See Table 1 for comparison of the displacement demands and limits.

Table 1 Displacement Demand and Limits Comparison

		Transverse			Longitudinal		
Bent No.	Total Height (ft)	Displ. Limit (in)	Δ_d (in)	Status	Displ. Limit (in)	Δ_d (in)	Status
1	N/A	8.0	6.0	OK	6.0	6.0	OK
2	35.5	14.2	6.0	OK	14.2	6.0	OK
3	N/A	8.0	6.0	OK	6.0	6.0	OK

Push-over analyses were performed to check substructure displacement capacities. The XTRACT program was used to compute moment-curvature relationship. Iterated hand calculations were prepared to compute the displacement capacities. Figure 6 shows the moment-curvature analysis results. Table 2 shows the displacement capacities and displacement demand comparison.

Section Details:

X Centroid: -10.36E-6 in
Y Centroid: -.3107E-3 in
Section Area: 400.0 in^2

Loading Details:

Constant Load - P: 56.00 kips
Incrementing Loads: Mxx Only
Number of Points: 30
Analysis Strategy: Displacement Control

Analysis Results:

Failing Material: Strand
Failure Strain: 35.00E-3 Tension
Curvature at Initial Load: 70.30E-9 1/in
Curvature at First Yield: .2138E-3 1/in
Ultimate Curvature: 2.568E-3 1/in
Moment at First Yield: 3391 kip-in
Ultimate Moment: 2849 kip-in
Centroid Strain at Yield: .8428E-3 Ten
Centroid Strain at Ultimate: 9.590E-3 Ten
N.A. at First Yield: 3.942 in
N.A. at Ultimate: 3.735 in
Energy per Length: 8.040 kips
Effective Yield Curvature: .2314E-3 1/in
Effective Yield Moment: 3670 kip-in
Over Strength Factor: .7763
EI Effective: 1.59E+7 kip-in^2
Yield EI Effective: -351.3E+3 kip-in^2
Bilinear Harding Slope: -2.214 %
Curvature Ductility: 11.10

Comments:

User Comments

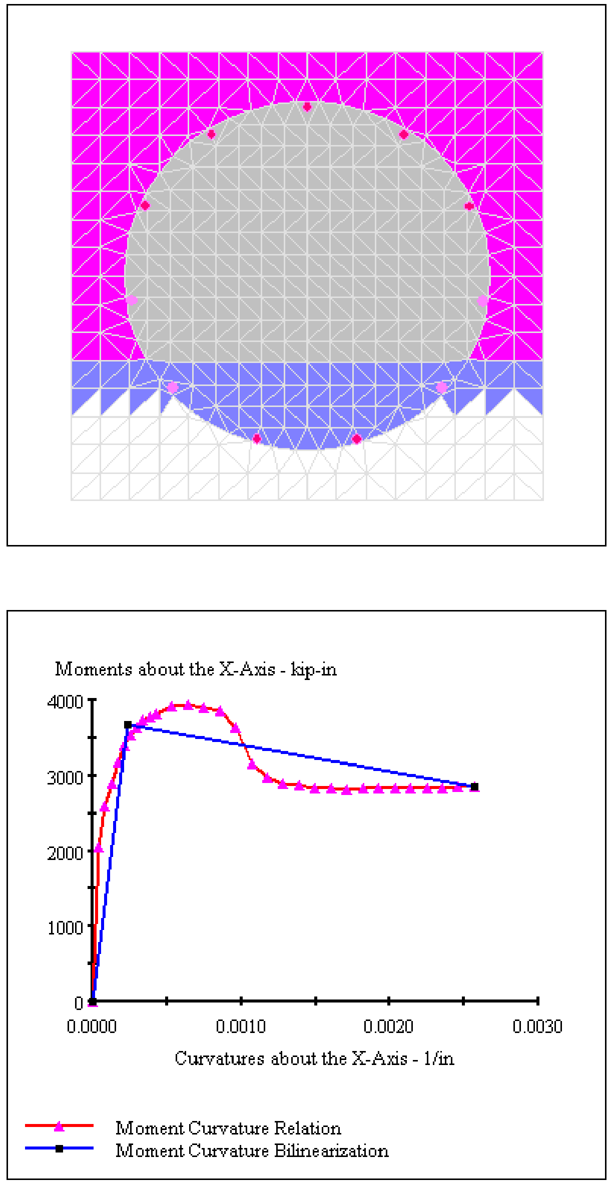


Figure 6 Precast Pile Moment-Curvature Analysis

Table 2 Displacement Demand and Capacity Comparison

	Transverse			Longitudinal		
Bent No.	Δ_c (in)	Δ_d (in)	Status	Δ_c (in)	Δ_d (in)[1]	Status
1	16.2	6.0	OK	15.2	6.0	OK
2	18.4	6.0	OK	21.2	6.0	OK
3	16.2	6.0	OK	15.2	6.0	OK

Further, ductility demands were computed and checked against the allowable ductility demand as prescribed in SCDOT Seismic Specs. For multiple column bents, the maximum allowable ductility demand for this bridge was determined as 8 based on SCDOT Seismic Specs. See Table 3.

Table 3 Ductility Demands

	Transverse				Longitudinal			
Bent No.	Δ_d (in)	Δ_y (in)	$\mu_{d\text{-}trans}$	Status	Δ_d (in)	Δ_y (in)	$\mu_{d\text{-}long}$	Status
1	6.0	2.7	2.2	OK	6.0	4.4	1.3	OK
2	6.0	3.2	1.9	OK	6.0	6.3	0.9	OK
3	6.0	2.7	2.2	OK	6.0	4.4	1.3	OK

Detailed calculations were performed for pile and bent cap connection, in which pile moment capacity, shear capacity, pile head bending and joint shears were analyzed. 20" square prestressed concrete piles are embedded 26 inches in the precast cap. Based on recommendation provided by Restrepo, J., 2011 and also Ziehl, et. al. 2011, 12 gage corrugated metal pipes are used to provide adequate shear friction and shear reinforcement to engage the precast concrete pile to develop sufficient pile-cap connection. The connection details are provided in Figures 7, 8 and 9.

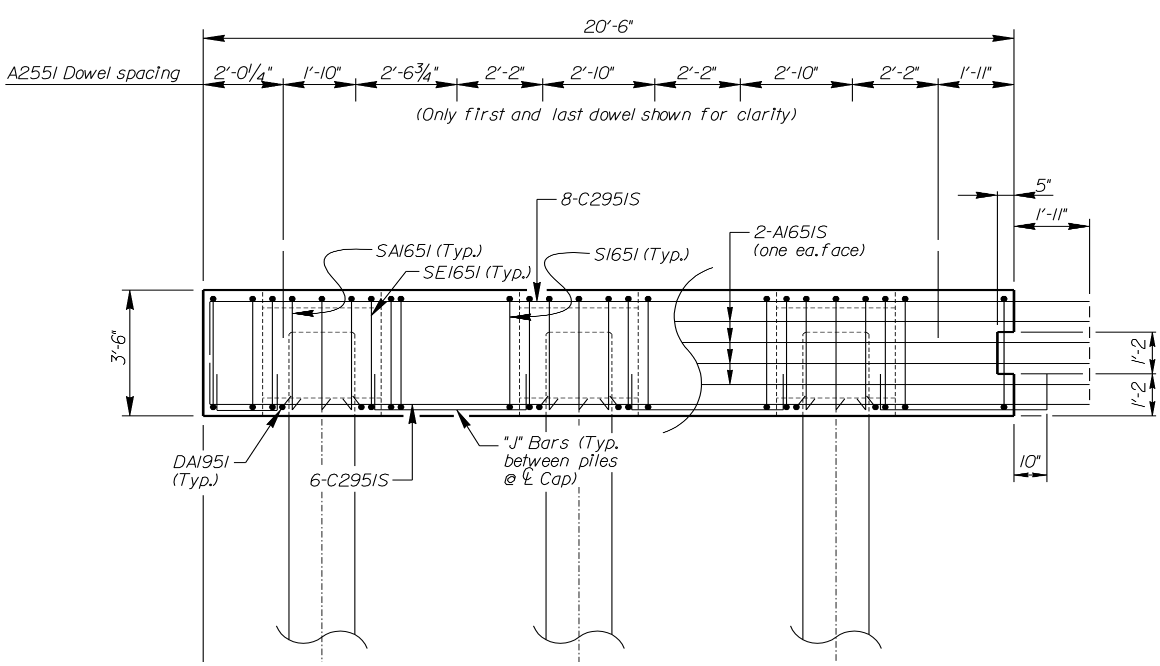


Figure 7 Bent Cap Elevation

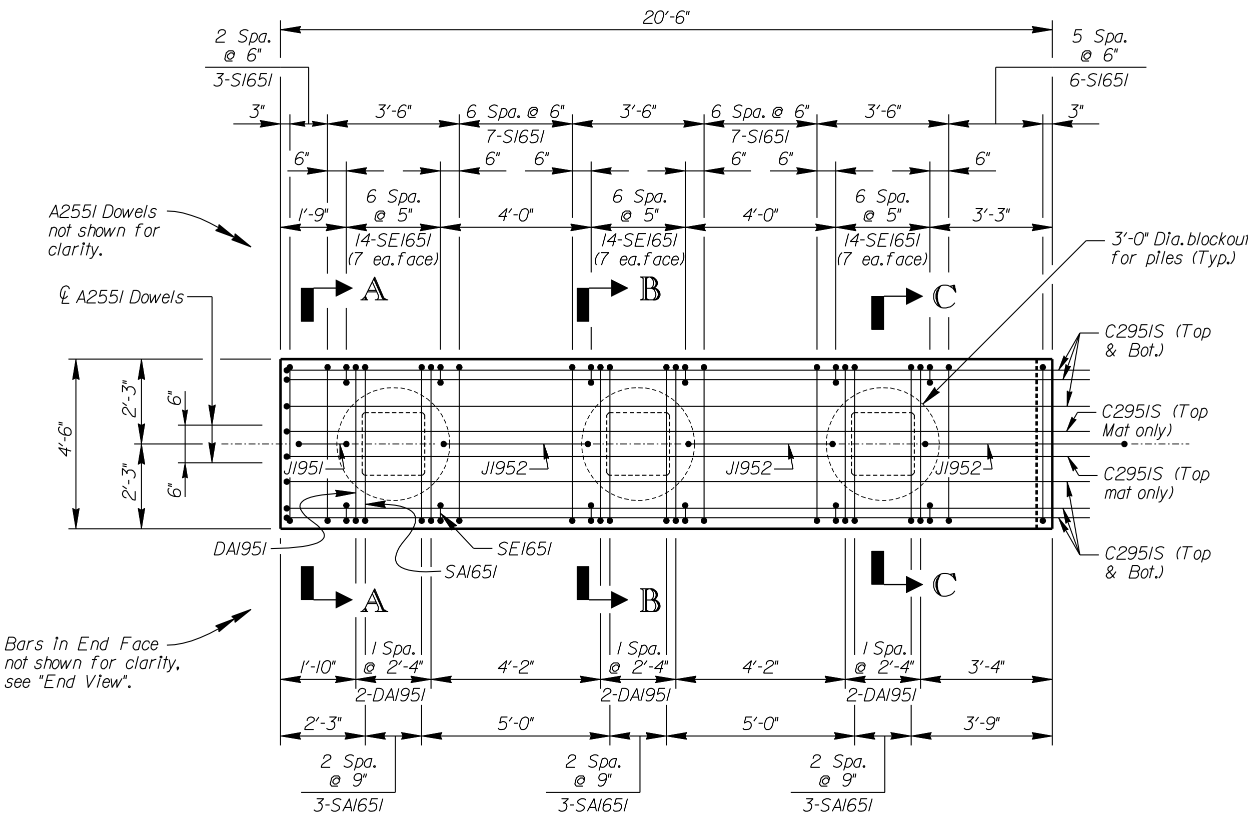


Figure 8 Bent Cap Plan

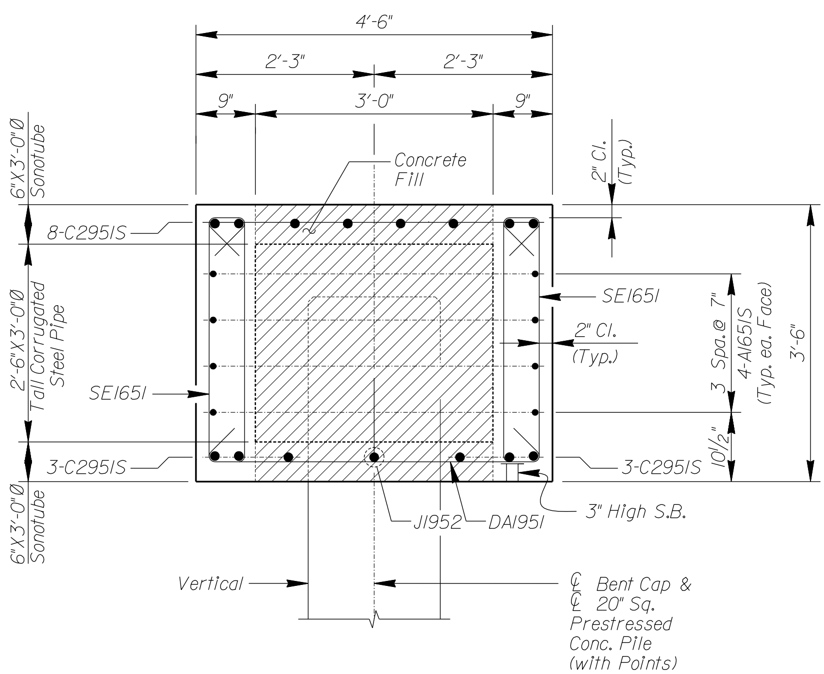


Figure 9 Bent Cap Cross-Section

3. Testing

The use of precast bent caps reduces construction time and costs; however, the connection between the cap and pile elements has not been standardized. The bent cap design incorporated the use of a plainly embedded connection between piles and precast bent caps. This connection is common in the state of South Carolina and for this project was the SCDOT preferred connection method. Given the new design provided by SVT Inc. and the relatively little knowledge related to the behavior of this connection the University of South Carolina developed a testing program which included two full-scale specimens.

Test specimens incorporated bent cap portions representing both interior (T joint) and exterior (Knee joint) sections of the cap design. By including both the T and Knee joint connections the University testing program was able to assess the behavior of the connection under a representative range of loading conditions and geometric limitations.

Each of the two bent cap elements was constructed with a 3 foot (0.9 m) diameter void about the pile embedment region. The void was designed such that both 18 and 20 inch piles (460 and 510 mm) including driving tolerances could be plainly embedded with this bent cap design. This void was cast with use of a sonotube 6 inches (150 mm) in height placed at both the top and bottom of the cap. The sonotube allowed reinforcement to pass through the void. The remaining 2.5 foot (760 mm) depth of the cap void was created with a 12 gauge corrugated steel pipe (0.11 inches [3 mm] thickness).

3.1 Piles

Precast prestressed piles used in the fabrication of the two tested specimens were designed according to typical pile specifications as provided by the South Carolina Department of Transportation, and were cast at Florence Concrete Products of Sumter, SC. Piles were 18 in. square in cross section and cast with a length of 16.5 ft. Piles were cast with sufficient length such that the pile inflection point would be incorporated into the experimental setup of each test specimen. Piles were prestressed with nine ½ in. diameter low relaxation strands with a guaranteed ultimate capacity of 270 ksi distributed in a circular pattern with a 13 in. radius. Strands were encased in a W6 spiral wire placed with a 3 in. turn spacing. At either end of the pile the spiral was terminated with 5 turns at a 1 in. pitch.

Each pile was instrumented with a single vibrating wire strain gage. These gages were placed 13 in. from the end of the pile. The 13 in. dimension from the pile end was equal to one half of the pile embedment depth. Gage placement was such that the direction of measurement corresponded to the direction of loading.

3.2 Bent Caps

The specimen representing an interior connection was constructed with dimensions of 7 ft x 4.5 ft x 3.5 ft. The 3 ft diameter pocket, in which the pile was to be embedded, was centered in the length of the specimen. The exterior specimen was constructed with the same 3.5 x 4.5 ft. cross section with a length of 6 ft. The cap pocket in this specimen was centered 3.5 ft from the interior end of the bent cap. The 2.5 ft overhang to the exterior end of the specimen helped to confine the embedded pile. Both precast caps were fabricated at Florence Concrete Products along with the piles.

Upon arrival of both pile and cap elements to the University of South Carolina the elements were connected through a closure pour. Piles were embedded into the bent caps to a distance of 26 in. The remaining void area of the cap pocket was filled with a normal weight concrete modified with a shrinkage reducing admixture. Previous research had shown positive results of such closure pours provided that the concrete used in the closure mix resulted in a compressive strength of at least 500 psi greater than the surrounding precast concrete. The closure pour was allowed to cure for a period of 28 days prior to the specimens being tested.

3.3 Experimental Setup

Due to the nature of seismic design practices in the state of South Carolina piles and connections at interior and exterior portions of a typical bent may undergo drastically different loading sequences. At interior joints piles are subjected to a constant state of axial compressive stress during seismic events. At exterior joints axial load may oscillate between compressive and tensile loading. The axial load magnitude and direction greatly affects the response of the connection (Ziehl et. al 2012). Additionally, at exterior connections, where a possible presence of detrimental axial tensile loading is present, geometric changes to the bent cap are also present. Previous research has shown that without proper detailing of this location premature failure may occur (Ziehl et. al 2012). To determine the behavior at both interior and exterior connections the experimental setup used for each specimen was varied.

The interior specimen was tested such that the longitudinal axis of the bent cap was held by a loading frame perpendicular to the strong floor. Cyclic displacements were applied to the pile at a distance of 146 in. from the face of the bent cap. The application of displacements at the 146 in. distance allowed for simulation of a pile inflection point. Displacements were applied with increasing magnitude from ±0.1 to ±8.0 in. corresponding to drift ratios between 0.1 and 5.5 percent. A constant compressive axial load of 50 k was applied to the end of the cantilevered pile. An overview of the experimental setup used in the testing of this specimen is shown in Figure 10a.

For exterior specimens, the specimen was oriented such that the longitudinal axes of both the bent cap and pile were parallel to the strong floor in a self-reacting fashion (Figure 10b). To prevent additional joint stresses the pile end was supported through a roller system. This consisted of the pile end being rested on a specially built steel plate with 4 roller bearings each rated for a load equal to the pile weight. The roller plate then rested on a lubricated steel plate providing minimal resistance through the range of motion of the pile tip.

To apply the variable axial load the hydraulic actuator used to apply displacements was connected to both the interior end of the bent cap and the pile at a distance of 92 inches from the bent cap soffit. In this manner displacements in what is termed the positive direction (axial tension) could be applied to the pile be extending the stroke of the actuator. Conversely, displacements in the opposite direction (negative) and axial compression was applied to the pile by closing or reducing the initial actuator stroke. The applied displacement protocol was maintained from the test of the interior specimen (Figure 11).

3.4 Results

The results of the two tests showed that the behavior of the connection was improved by the SVT Inc. design when compared to the traditional cast in place bent caps currently in use by the SCDOT. This improvement is shown in a number of features of the gathered results. Comparison to specimens constructed with cast in place bent caps is made with results reported by Ziehl et al. 2012. In that report specimens were tested and instrumented in the same manner as those described here.

The connection of a plainly embedded pile should develop an appreciable moment capacity to transfer seismic forces and maintain an adequate displacement ductility capacity as defined by the SCDOT while the connected bent cap remains within the elastic regime. In order to maintain the elasticity of the bent cap the embedded pile is required to develop a plastic hinge in the region just below the cap soffit.

3.5 Moment Capacity

The moment versus displacement behavior of each of the two specimens is shown in Figures 12a and 12b. The results indicate that the capacity of these two test specimens exceeds that obtained by previously tested cast-in-place specimens. This is true for both the magnitude of the moment developed and the displacement at which that ultimate moment occurs.

The interior specimen developed an ultimate moment capacity of 3,060 k-in. at a displacement of 3.5 in. Comparatively, the maximum moment developed during the testing of 4 interior specimens constructed with a cast-in-place bent cap was 2,930 k-in. Additionally the interior specimen obtained an experimental moment capacity greater than that predicted through a detailed moment curvature analysis, the results of which are shown in Figure 12a.

The exterior specimen also obtained an experimental moment capacity of a greater magnitude than the predictive model (Figure 12b) or similar cast-in-place bent cap test specimens. This specimen achieved a moment capacity of 2,280 k-in. while a similar specimen achieved a maximum moment of 2,050 k-in.

3.6 Ductility

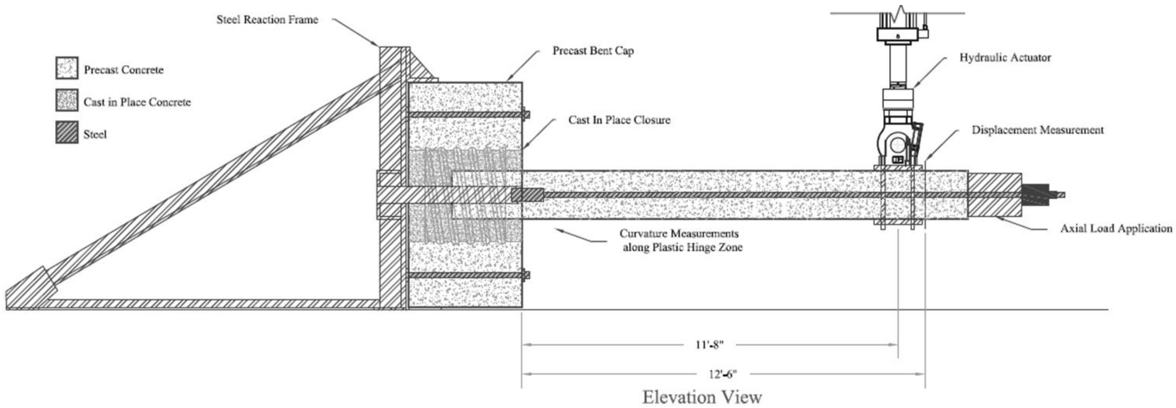
The required displacement ductility behavior was reflected in the connection behavior of the two test specimens. The ductility response of each specimen exceeded the required response as determined by the SCDOT. The specimens developed ductility capacities of 8.2 and 13.3 in the interior and exterior specimens respectively. The SCDOT requires a displacement ductility capacity of 8.0.

3.7 Embedment Depth and Confining Stress

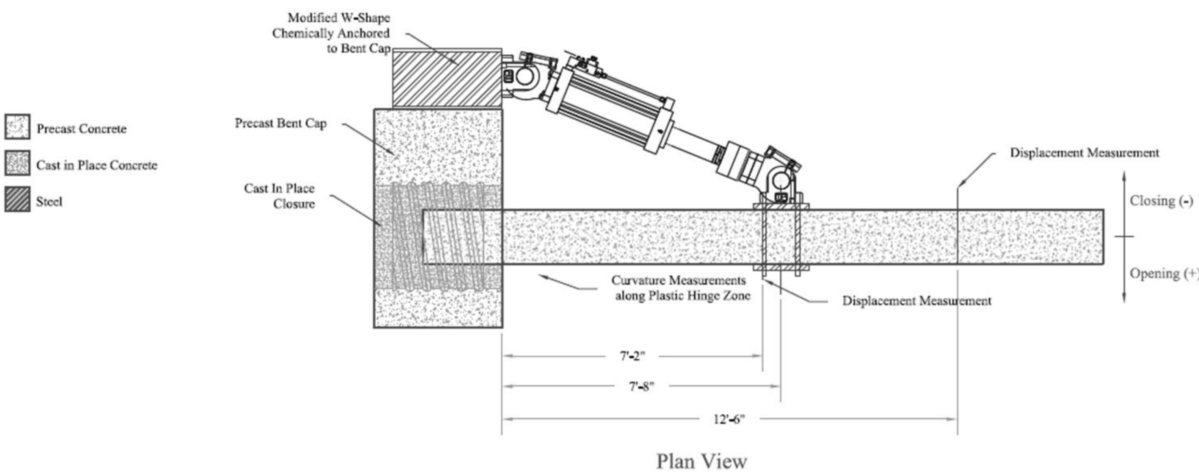
The provided embedment length of 26 in. (1.4xSmallest cross section direction) was sufficient to develop a plastic hinge in the desired zone below the bent cap soffit. In both the interior and exterior specimen the developed plastic hinge length was estimated to be greater than the prescribed 18 in. dimension according to the SCDOT seismic design specifications. The resulting plastic hinge length speaks to both the design of the connection as well as the pile embedment length. With sufficient embedment length a confining stress (also known as clamping force) exerted by shrinking concrete surrounding the embedded pile aids in the bond and development of prestressing strands within the pile. The confining stress is a factor of the pile/bent cap dimension, shrinkage strain of the concrete in the bent cap, Poisson ratio's and Young's modulus of the concrete used in the bent cap (ElBatanouny and Ziehl 2012). This clamping force allows the pile embedment length to be much shorter than the development length of the prestressing strand as it increases the friction between the prestressing strands and the surrounding concrete. If not sufficiently developed, strand slip is expected when the pile is subject to large lateral forces. The slip results in concentration of damage and cracking. Typically damage is concentrated at the interface between the bent cap and pile.

In the case of the two specimens tested each pile was instrumented with the previously described vibrating wire strain gages. By measuring the change in strain before casting the closure pour and prior to testing, the confining stress on the pile was calculated (ElBatanouny et al. 2012). Further, by measuring following the completion of testing, the gage measurements were able to show that the confining stress was maintained throughout testing (Figure 13). This result is significant because it has been speculated that the confining stress on which the connection relies may dissipate as a result of damage from seismic loading.

This project aimed to test details of a precast bent cap to be connected to precast prestressed piles via a plain pile embedment. Based on similar research conducted at USC both interior and exterior connections and relative portions of the cap were tested (Ziehl et. al 2012). Specimens were test with an embedment of 1.4 pile diameters (26 in.) shown previously to achieve desired behavior in CIP bent cap systems (Ziehl et. al). Specimens were evaluated based on moment capacity, ductility and performance of the bent caps. Both specimens performed well in terms of cracking of the bent cap or connection region. Both specimens also achieved desired ductility behavior reaching capacity levels of 8.2 and 13.3 between interior and exterior specimens respectively. While both specimens performed similarly while subject to axial compression in terms of moment capacity, the reported behavior of the exterior specimen is given on the tensions side which reached 75% of that during compression. Ultimately each specimen performed well in the laboratory and was recommended for use by USC.



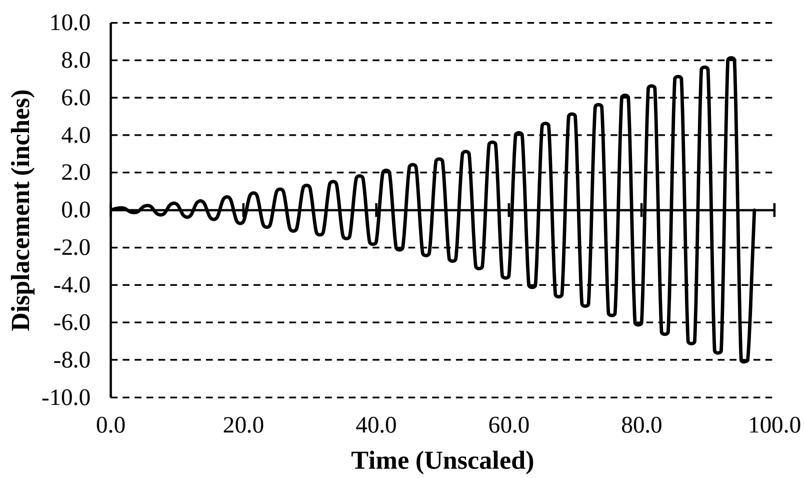
a) Interior specimen experimental setup



b) Exterior specimen experimental setup

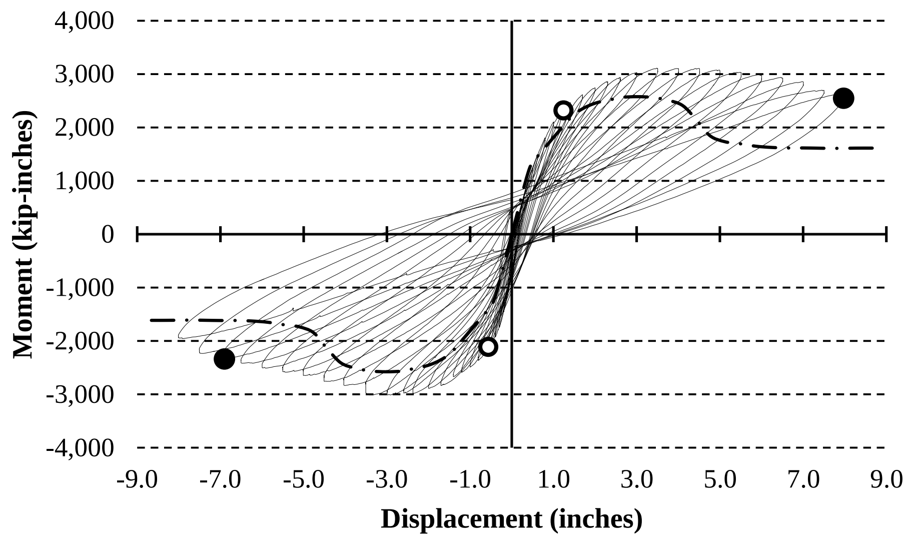
Metric (SI) conversion factors: 1 in. = 25.4 mm

Figure 10 - Experimental Setups

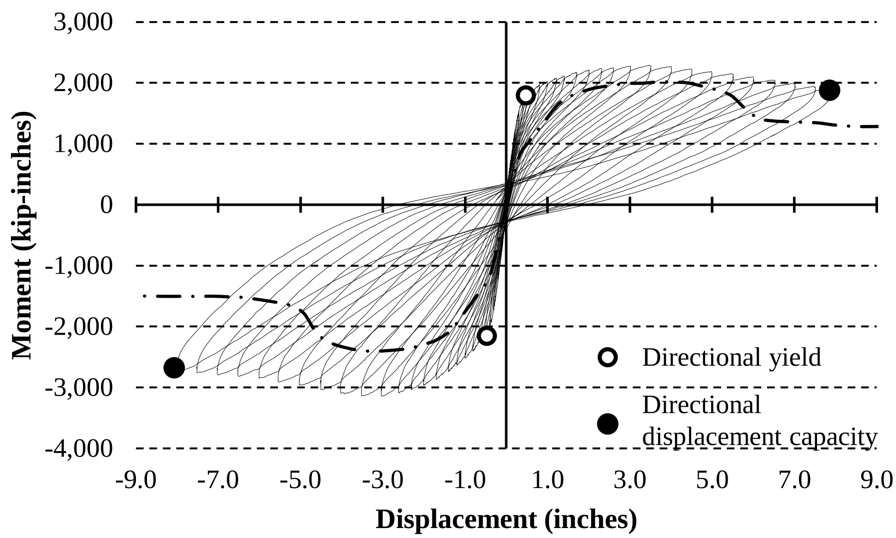


Metric (SI) conversion factors: 1 in. = 25.4 mm

Figure 11 - Displacement versus Time (generalized)



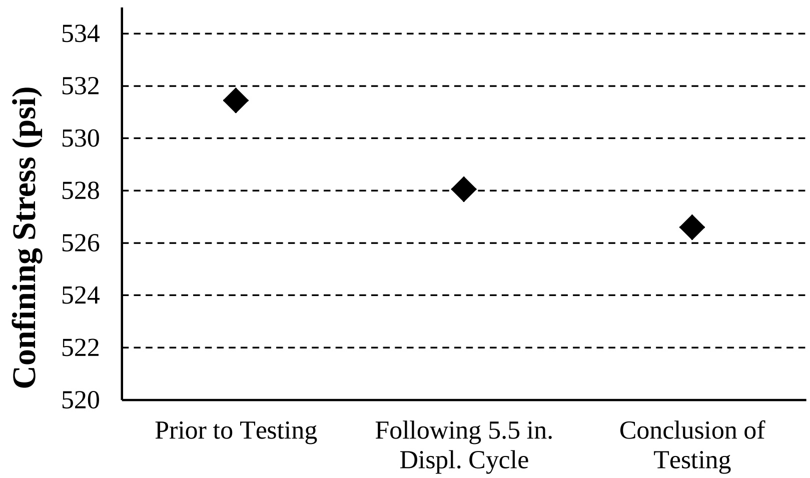
a) Interior specimen



b) Exterior specimen

Metric (SI) conversion factors: 1 in. = 25.4 mm; 1 kip-in. = 0.11298 kN-m.

Figure 12 - Moment versus Displacement Behavior



Metric (SI) conversion factors: 1 psi = 6.895 pa

Figure 13 - Exterior Specimen: Confining Stress during Testing

4. Conclusion

Rapid construction method will be utilized on this project. Both superstructure and substructure consist of precast components to expedite the construction process and minimize the impact to adjacent properties. Precast solid slabs will be post-tensioned in transverse direction and made continuous for live load in longitudinal direction. Substructure units consist of precast bent caps and prestressed concrete piles. Based on design and testing, it was found that plainly embedded pile/cap connection with embedment depth of 1.4xSmallest cross section direction (26 in.) is capable of developing adequate shear and moment capacity and providing sufficient ductility capacity. Although the design presents some challenges in controlling construction tolerance for installing the precast concrete piles to fit in the pocket holes, it is SCDOT's opinion that this type of rapid construction is favorable to reduce construction time and minimize impact to adjacent properties.

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